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RESEARCH MEMORANDUM

AERODYNAMIC CONTROL OF SUPERSONIC INLETS FOR OPTIMUM PERFORMANCE

By Fred A. Wilcox and Eugene Perchonok

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

AERODYNAMIC CONTROL OF SUPERSONIC INLETS FOR OPTIMUM PERFORMANCE

By Fred A. Wilcox and Eugene Perchonok

SUMMARY

Aerodynamic means of controlling a translating spike and a variable bypass of supersonic inlets are discussed. These include determination and use of normal-shock position, oblique-shock position, and diffuser-exit Mach number as control parameters. Although the discussion is limited to axisymmetric inlets, these same control parameters can be used for a single side inlet feeding a turbojet engine, the translating spike being replaced by a variable-ramp compression surface.

INTRODUCTION

Variable-geometry inlets for turbojet engines at supersonic flight speeds offer improvement in over-all performance over the fixed inlet. The translating spike and the variable bypass are two variable features commonly considered for the axisymmetric inlet. The spike is used to spill excess air behind the oblique shock when the engine requires less air flow than the inlet provides, or it may be employed to optimize inlet performance by maintaining the oblique shock near the cowl lip when a bypass is used for air spillage. Air spillage by either translating the spike or opening the bypass results in less drag than spillage behind the expelled normal shock of a fixed inlet.

In order to attain the best possible performance, these variable-geometry features must be properly positioned. Control systems to provide optimum settings must be supplied with input signals which are representative of the desired inlet performance and, in addition, lend themselves to control application.

The purpose of this paper is to discuss and evaluate some of the input signals or control parameters which have been experimentally employed to operate turbojet inlet-control systems. These include the normal-shock position, the oblique-shock position, and the diffuser-exit Mach number. The discussion is based on results obtained at the

NACA Lewis laboratory during control investigations of ram-jet engines (refs. 1 to 5) and during a study on the control of a supersonic inlet for the J34 turbojet engine (refs. 6 and 7).

SYMBOLS

H pitot pressure, lb/sq ft abs

M Mach number 4010

p static pressure, lb/sq ft abs

θ_l angle between line connecting spike tip and cowl lip and inlet center line, deg

θ_s angle formed by inlet oblique shock with inlet center line, deg

Subscripts:

r reference

s sensing

0 free stream

2 diffuser exit, station immediately ahead of bypass

DISCUSSION

A typical variable-geometry supersonic inlet for a turbojet engine is shown schematically in figure 1. The control parameters to be discussed are also listed in this figure. With any supersonic inlet, the position of the inlet normal shock is a reliable indication of inlet performance. Optimum performance for inlets of the type shown is generally obtained with the normal shock at or near the cowl lip. Determination of normal-shock position will thus provide a useful inlet control parameter.

A convenient way of determining normal-shock position is by measuring its static-pressure rise. Three techniques for measuring the normal-shock pressure rise are shown in figure 2. The spike static wall orifice is located on the center body in the plane of the cowl lip. The probe static orifice is located on a small probe extending slightly ahead of the cowl lip. A backward-facing pitot tube is located somewhat inside the cowl. In each case a reference orifice is located forward on the spike surface out of the region of influence of the normal shock. Details of these orifices are given in figure 3. The differential pressure between the sensing and reference orifices is used as the control input signal. In figure 2, this differential pressure has been nondimensionalized by dividing by the free-stream static pressure to generalize the parameter and thus make it independent of altitude.

Values of this parameter are plotted for normal-shock positions ahead of and behind the plane of each sensing orifice in terms of percent change in diffuser-exit corrected air flow. With the use of the spike static wall orifice as sensor (ref. 2), the parameter is essentially zero when the shock is downstream of the orifice. As the shock moves forward and crosses the sensing orifice, the static pressure at the sensing orifice rises and causes the value of the parameter to rise. A desired value for the parameter is selected along this rise and a control system is designed to maintain this value. If the measured differential pressure is greater than the setting, air spillage is increased and thus moves the normal shock downstream. If the measured differential is less, spillage is decreased and the normal shock is moved upstream. If the control setting is made at a value of the parameter other than zero, compensation for altitude changes must be provided.

Owing to both normal-shock curvature and boundary-layer growth along the spike, the spike static orifice signals a normal-shock position at which some normal-shock air spillage exists. This means that to obtain critical inlet operation, the orifice would have to be moved somewhat downstream of the lip plane. This difficulty is not experienced with the probe static sensor, and, in addition, movement of the orifice with spike translation is avoided. The data for the probe static sensor (ref. 7) indicate a sharp rise in the parameter at the control point. Such an input signal provides close control of normal-shock position. However, if the slope of the parameter becomes too steep, control-system oscillation may result.

An even greater rise in differential pressure is obtained with the backward-facing total probe. For downstream shock locations, the value of the parameter falls well below zero. If the control setting is made at zero, the necessity of measuring p_0 and providing altitude compensation is avoided. The backward-facing total probe thus provides a signal having the desirable features of both a steep slope near the control setting and no need for altitude compensation.

At low supersonic flight Mach numbers, difficulties are sometimes experienced with normal-shock sensing systems. For some diffuser designs, the normal shock will not enter the cowl because of excessive internal contraction. In other cases, the normal shock will enter the cowl but a shock detaches from the external cowl surface. As illustrated in figure 4 this detached wave interferes with the static probe, resulting in little change in the value of the control parameter as the normal-shock position varies. For such an inlet, the backward-facing total probe provides a more usable signal, primarily because of its location away from the influence of the detached wave. Again no altitude compensation is required since the control setting may be made at a parameter value of zero.

If a translating spike is used for flow spillage, the inlet oblique 4010
shock may at times fall either inside or outside the cowl lip. The variation in normal-shock position parameter for the probe static orifice and the backward-facing total probe for these extreme positions of the oblique shock is shown in figure 5. The backward-facing total probe provides a parameter passing well below zero for both cases. The value of the parameter for the probe static orifice shifts upward when the oblique shock falls ahead of the cowl. This is believed caused by the combined effects of the static-pressure rise across the oblique shock and by misalinement of the probe with the local flow.

The results of applying normal-shock position sensing to control of a translating spike are given in figure 6. The data were obtained at $M_0 = 2.0$ with a J34 engine installed in an axisymmetric pod-mounted nacelle. An electric actuator was used to position the spike. The current to the actuator was controlled by the voltage output of a pressure transducer connected between a static probe and its reference orifice. In order to achieve a variation in spillage air flow, the engine speed was varied from 9,210 to 11,630 rpm. The solid line represents the spike position angle required for critical inlet operation. The data points represent the spike position set by control. The data show that the control set the spike position within 1° of that required for critical inlet operation.

Besides being used to spill air, the spike can be used to optimize inlet performance by keeping the inlet oblique shock near the cowl lip over a range of flight Mach numbers when a bypass is employed to spill the excess air. A way in which the oblique-shock position can be determined and set at the cowl lip is shown in figure 7. Two pitot tubes are used, one a sensing tube at the cowl lip and the other a reference tube at the spike tip. The difference between the pressure measured by each tube provides the control signal. This difference in pressure is again divided by free-stream static pressure to nondimensionalize the parameter and make it independent of altitude. The oblique-shock position error plotted in figure 7 is defined as the difference between spike position angle and conical shock angle. If the oblique shock falls within the cowl, the oblique-shock parameter is essentially zero because both tubes read total pressure behind a free-stream normal shock. As the oblique shock passes in front of the cowl lip, there is a rise in the oblique-shock parameter because the loss in total pressure across the oblique and normal shocks ahead of the cowl-lip pitot tube is less than the total-pressure loss across the single normal shock of the spike pitot tube. The analytically computed rise is in agreement with the measured value. Details of the sensing pitot tube used are given in figure 8.

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A value of the oblique-shock position parameter is selected to be maintained by the control system. The data indicate that a control system based on this parameter can hold the oblique-shock position angle to within a fraction of a degree by retracting the spike when the oblique shock falls outside the cowl and extending the spike when the shock falls inside the cowl.

Consideration has been given the problem of obtaining effective control input signals for shock positioning systems when the inlet is operated at an angle of attack. By locating the sensing and reference orifices on the horizontal center line of the inlet, satisfactory control has been obtained for both oblique- and normal-shock sensing systems up to 10° angle of attack, the maximum investigated (refs. 2 and 5).

The techniques described for positioning the normal shock by translating the spike can also be applied to the control of the bypass discharge area. Experimental results for such a system are shown in figure 9. The bypass was actuated with a hydraulic servo system, and the control input signal was provided by a static orifice probe located at the cowl lip. The solid lines in the lower half of the figure represent diffuser performance at $M_0 = 1.8$ and 2.0 with the spike positioned at the θ_l values indicated. Values for the normal-shock position parameter provided by the probe static orifice are given in the upper part of the figure. Although the slope of the normal-shock position parameter is very steep at the control setting selected, satisfactory action was obtained without hunting of the control system. (See ref. 7.) The steady-state points set by the control are indicated by the data points which fall within 1.5 percent of the desired corrected air flow. This scatter is the approximate accuracy of air-flow measurement.

The response of this control system to manual displacement of the bypass away from the control setting was also satisfactory. When the bypass was closed from an initial control position of one-half open by manually overriding the control, the inlet operating point was taken into a region of heavy pulsing. When the control was turned on, it restored the desired operating condition to 90 percent of the displacement in 0.22 second and permitted only 3 cycles of pulsing. It did this in spite of the fact that during the pulsing cycle the normal shock was intermittently passing the sensing orifice. Satisfactory action was also obtained when the bypass was manually opened, placing the operating point in the supercritical region to the right of the control point.

The third control parameter to be considered is the diffuser-exit Mach number M_2 which has application primarily in the control of the bypass. In the lower part of figure 10, the diffuser pressure recovery is shown as a function of diffuser-exit Mach number, defined as immediately ahead of the bypass. The diffuser discharges through parallel outlets, the engine, and the bypass. At a given stream Mach number, peak diffuser performance occurs at only one value of exit Mach number. Since the exit Mach number is a function of diffuser-exit corrected air flow, M_2 can be held at the desired value as the engine air flow varies by changing the amount of air spilled through the bypass. The ratio of static pressure to total pressure at station 2 is representative of the value of exit Mach number and is the control parameter selected. The variation of this ratio with diffuser-exit Mach number, plotted in the upper part of figure 10, is continuous and is readily adapted to control design.

By comparing the measured pressure ratio to a desired ratio (control setting, which must be scheduled with flight Mach number), the exit Mach number can be set and maintained at a desired value. If the measured ratio is greater than the control setting, the bypass is opened to increase the diffuser air flow and the exit Mach number. If the measured ratio is less, the bypass is closed and therefore the exit Mach number is reduced. With turbojet engines, the diffuser-exit Mach number is sufficiently great to give reasonable accuracy in determining the pressure ratio.

The data points in figure 10 were set with a control system in which the pressure ratio was measured electrically with pressure transducers and the bypass actuated by a hydraulic servo system. The scatter in the data points corresponds to ±5.3 percent of diffuser corrected air flow and was the result of using a single tube to measure diffuser-exit total pressure. Shifts in total-pressure profile with engine operating condition caused this single measurement to deviate from the average. It thus appears necessary to use some means of total pressure averaging for this control signal.

CONCLUDING REMARKS

Although the discussion is limited to axisymmetric inlets, these same control parameters can be used for a single side inlet feeding a turbojet engine, the translating spike being replaced by a variable-ramp compression surface. The twin-duct arrangement presents new problems.

There is a need in this relatively new and rapidly expanding field of inlet control to find new inlet-control parameters as well as to improve the techniques of using the existing ones. Much of this can be done with properly instrumented scale tests of the inlet alone. Work is continuing at the Lewis laboratory on such inlet models as well as on the full-scale inlet-engine combination.

4010 Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 1, 1955

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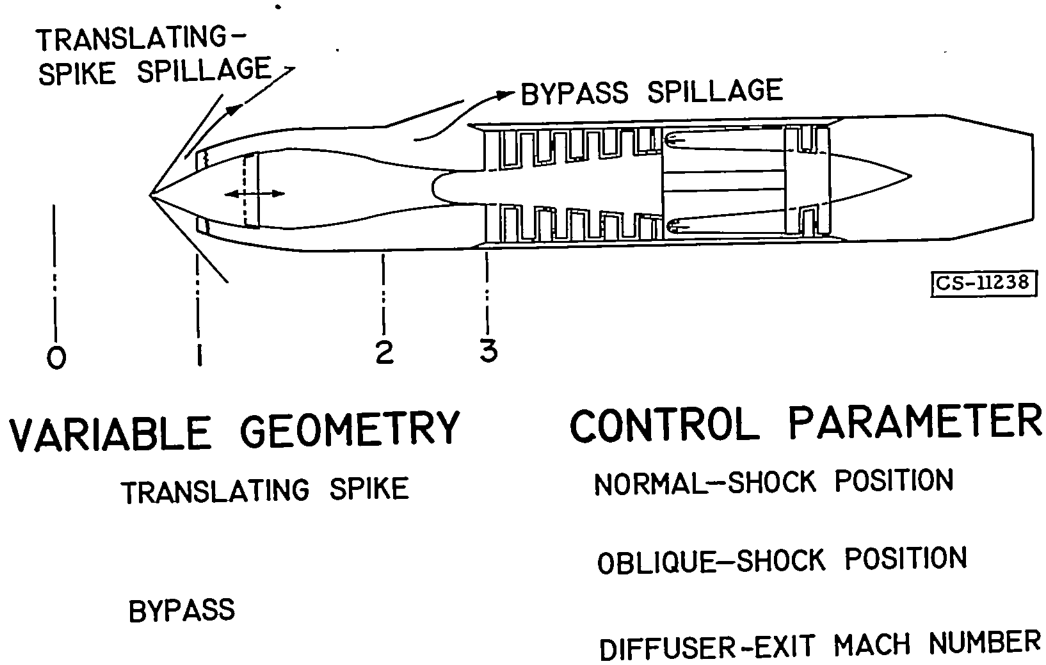


Figure 1. - Schematic diagram of typical variable-geometry supersonic inlet for turbojet engine.

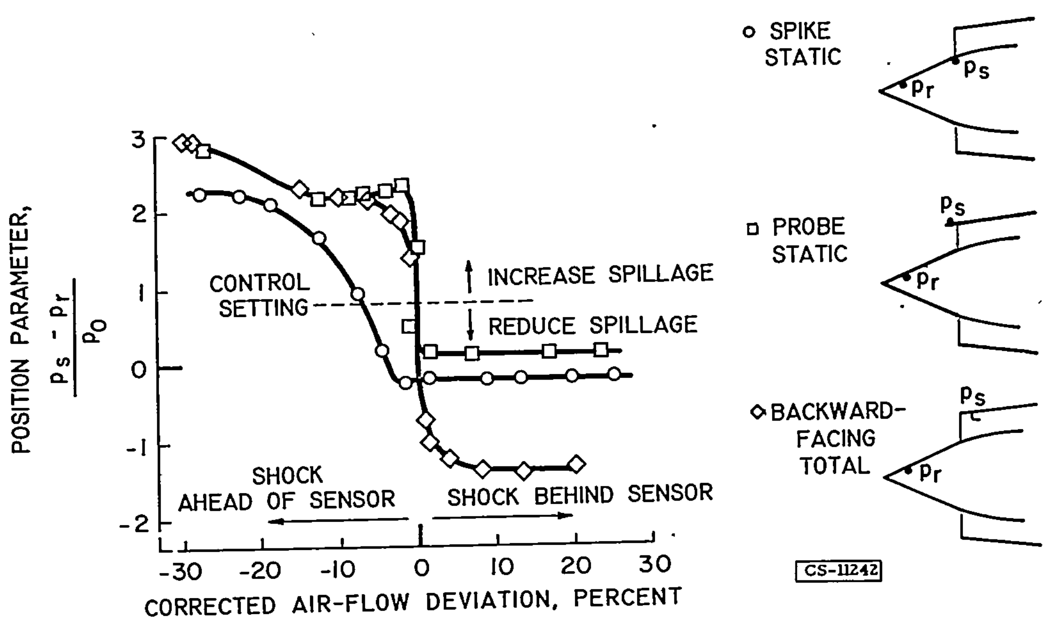
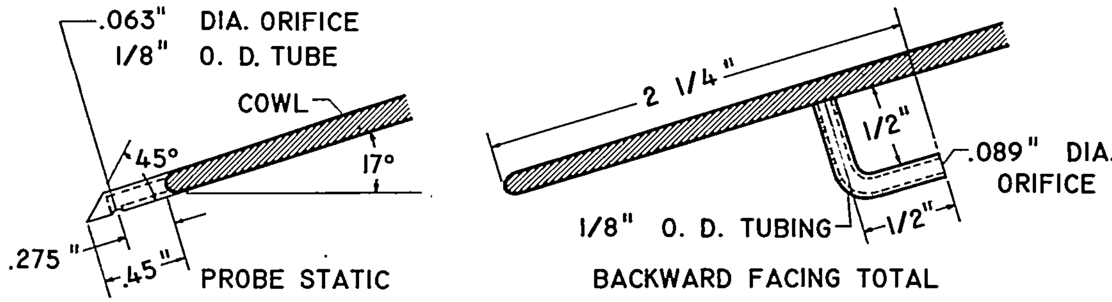
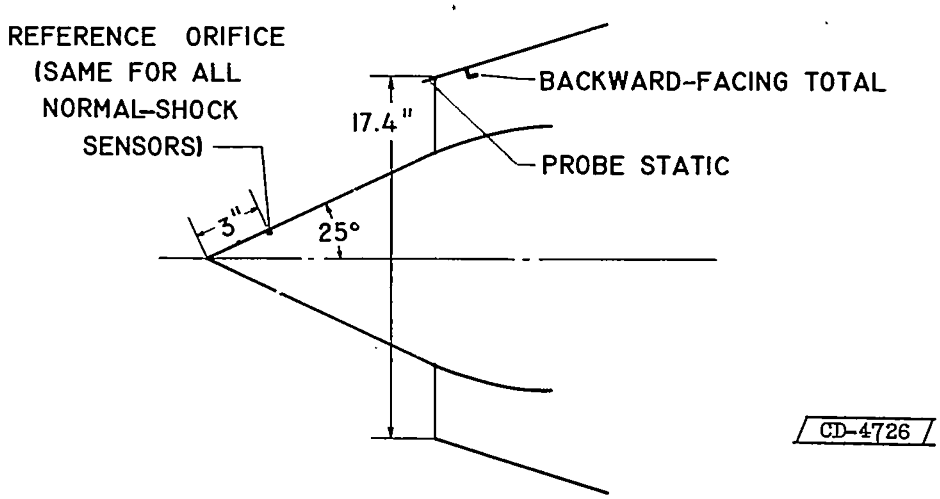


Figure 2. - Normal-shock position sensing with oblique shock at cowl lip. Free-stream Mach number, 2.0.



(a) DETAILS.



(b) INSTALLATION ON COWL.

Figure 3. - Installation details of probe static and backward-facing total probe.

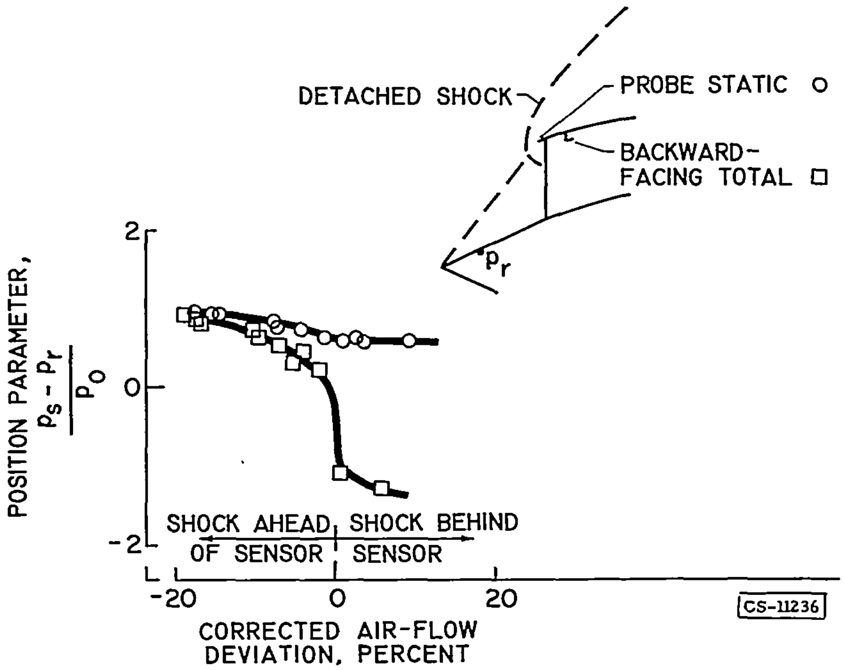


Figure 4. - Effect of detached wave. Free-stream Mach number, 1.6.

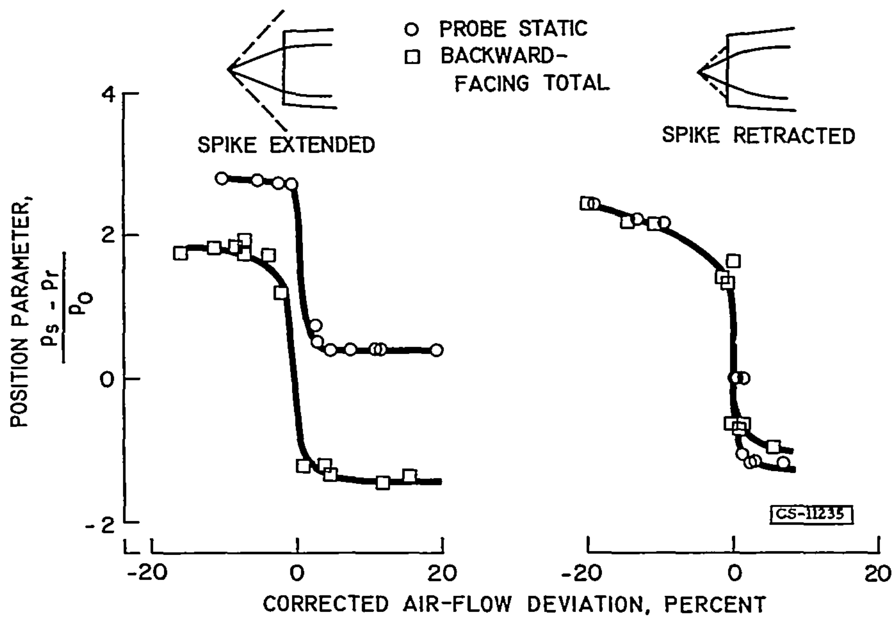


Figure 5. - Effect of oblique-shock position. Free-stream Mach number, 2.0.

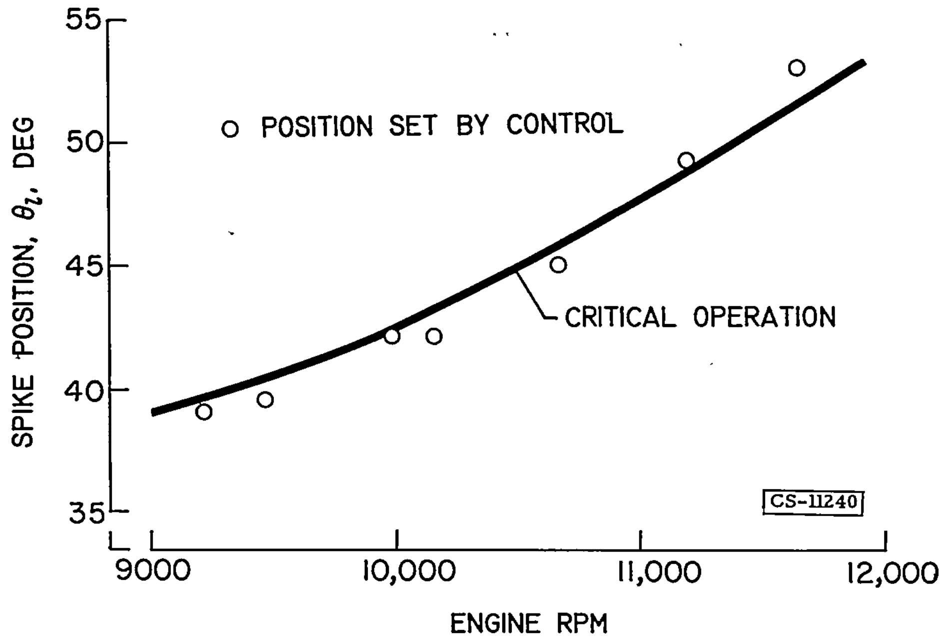


Figure 6. - Normal-shock position sensing applied to control of translating spike. Free-stream Mach number, 2.0.

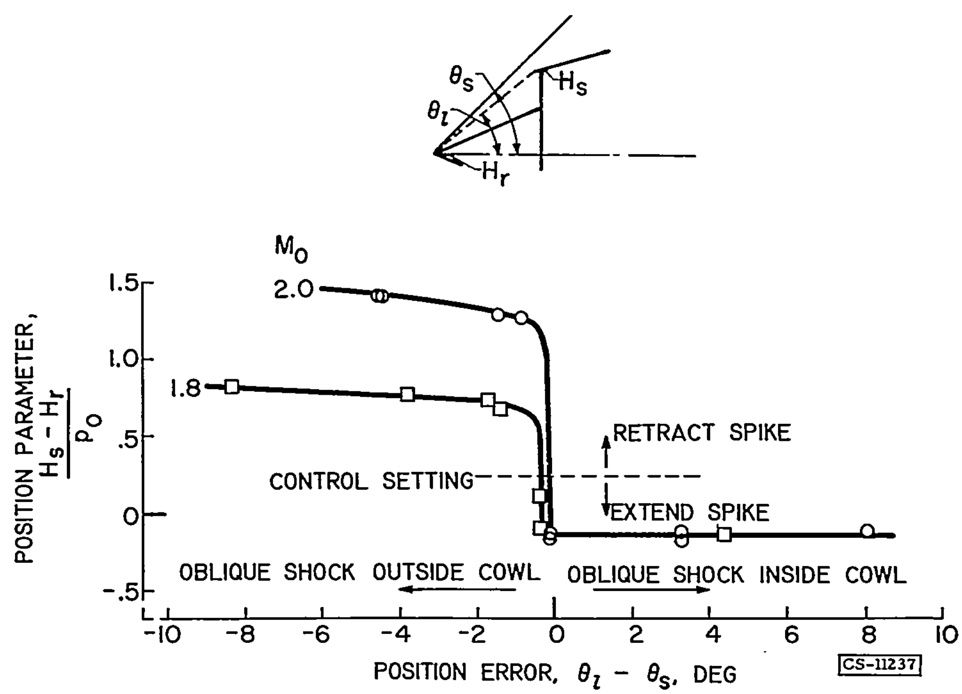
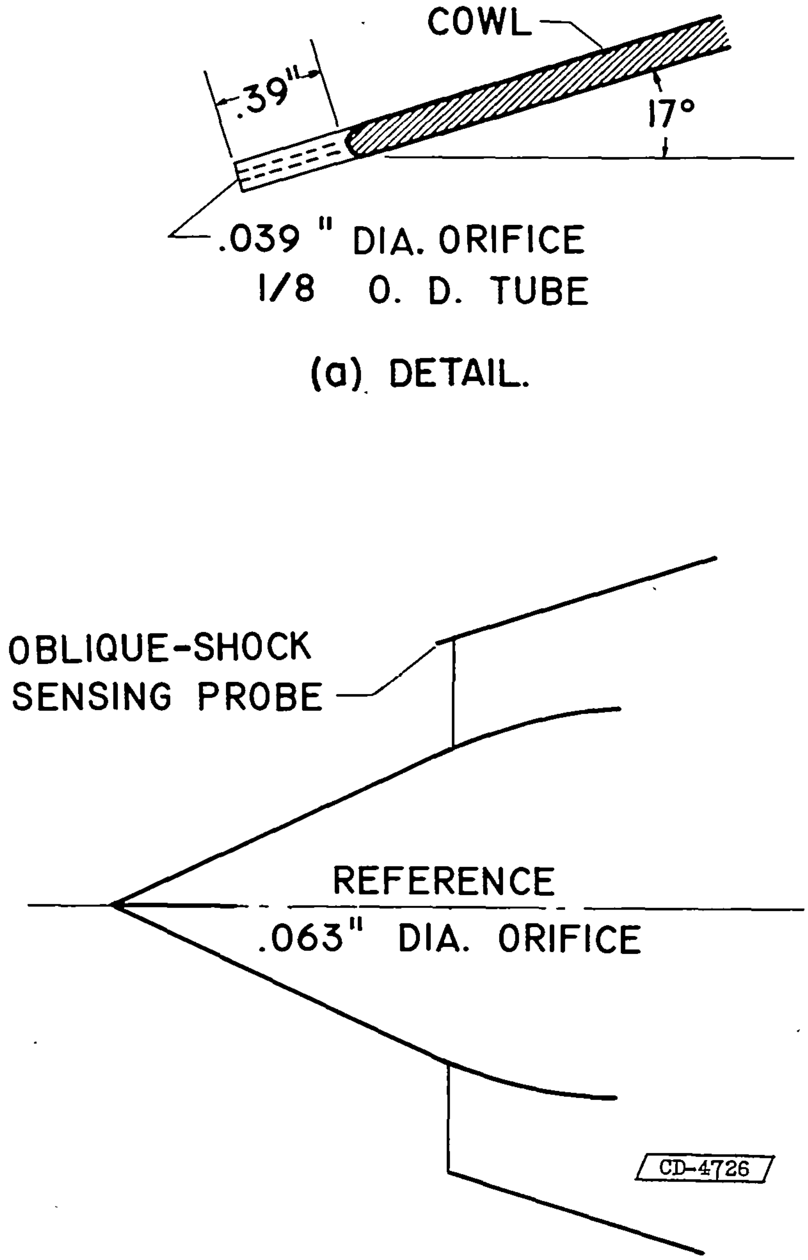


Figure 7. - Oblique-shock position sensing.

OBLIQUE - SHOCK POSITION SENSOR



(b) INSTALLATION ON COWL.

Figure 8. - Pitot tube sensing oblique-shock position.

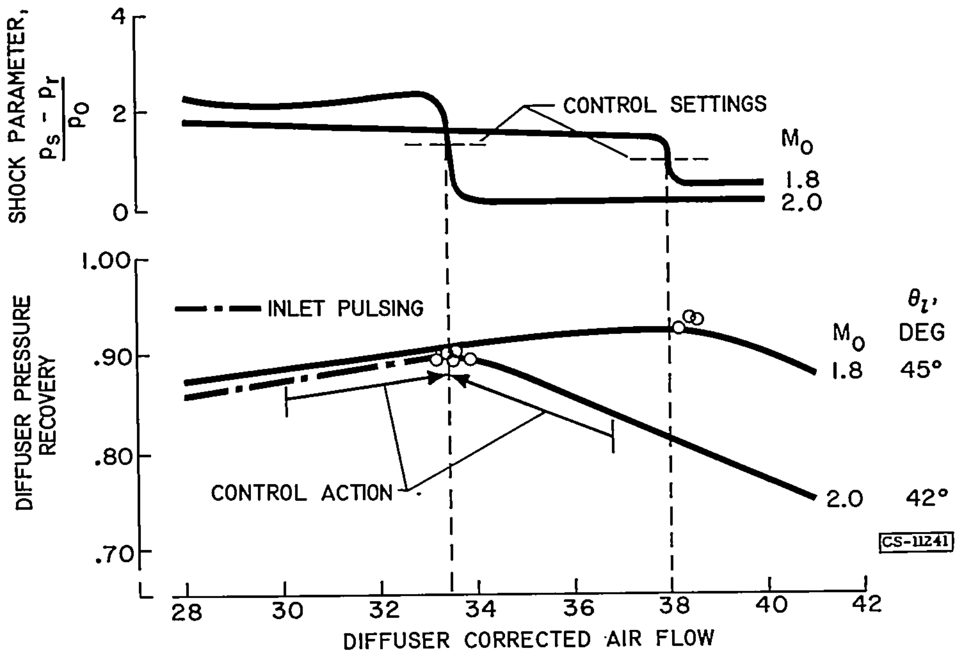


Figure 9. - Control of bypass by normal shock. Probe static sensor.

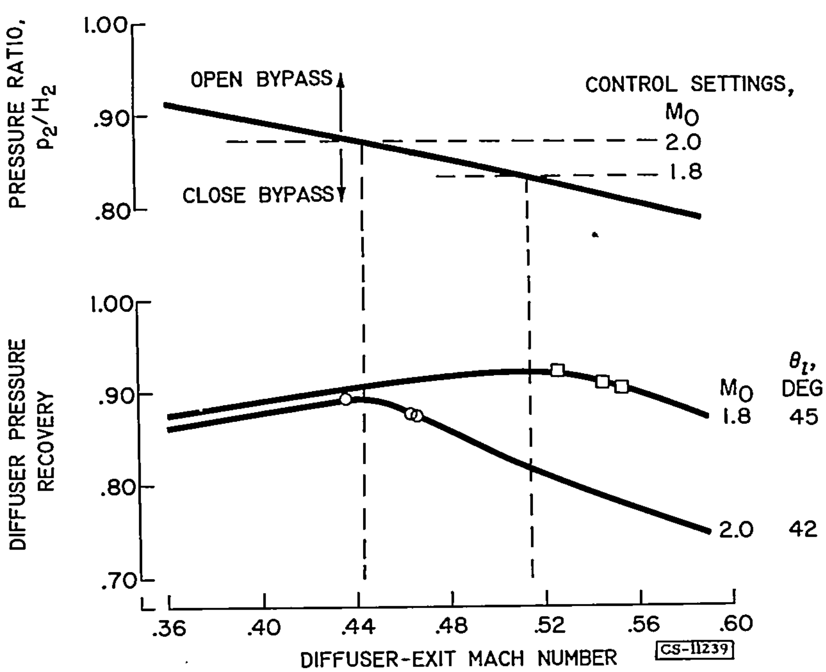


Figure 10. - Control of bypass by diffuser-exit Mach number.

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